1971-09

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http://hdl.handle.net/10945/15729

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# THESIS

FURTHER VERIFICATIONS OF AND EXPERIMENTS TO IMPROVE THE MODIFIED HATRACK SCHEME FOR FORECASTING THE MOTION OF TROPICAL CYCLONES

by

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September 1971

# Further Verifications of and Experiments to Improve the Modified Hatrack Scheme for Forecasting the Motion of Tropical Cyclones

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY

from the

NAVAL POSTGRADUATE SCHOOL
September 1971

ABSTRACT

The MODIFIED HATRACK (MODHATR) scheme for forecasting tropical cyclone motion consists of a numerical steering component using geostrophic winds derived from Fleet Numerical Weather Central's SR height field to steer the storm center, and a statistical modification component to correct for bias and improve forecast accuracy. MODHATR forecasts from the 1969 and 1970 North Atlantic hurricane seasons are analyzed, and average errors presented and compared to earlier years' results. MODHATR forecasts are shown to be superior on the average to OFFICIAL forecasts, NHC-67, and TYRACK forecast schemes for forecast intervals to 48 hours, with relative accuracy of MODHATR decreasing with time.

Results of an experiment to improve the statistical correction for bias are reported. A level- and mode-selection scheme is investigated which offers some promise of improving forecast accuracy at later forecast intervals. A comparison is made between warning-time and synoptic-time initial-position errors showing synoptic-time positions to be more accurate for initiating MODHATR forecasts.

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## ACKNOWLEDGEMENTS

The author wishes to thank Professor Robert J. Renard, faculty advisor, for his valuable assistance and guidance during the preparation of this paper.

Appreciation is also extended to Fleet Numerical Weather Central, Monterey, California, Fleet Weather Central, Norfolk, Virginia, Fleet Weather Facility, Jacksonville, Florida, and the National Hurricane Research Center, Miami, Florida, for furnishing data used in the paper.

# I. INTRODUCTION AND BACKGROUND

Renard (1968) initially reported on the results of experiments with a numerical-statistical scheme for forecasting the motion of tropical cyclones. The numerical portion of the system, known as HATRACK, utilizes geostrophic winds derived from the Fleet Numerical Weather Central's (FNWC) smoothed height field (i.e., the SR height field) as a steering current. A correction for the bias of the steering current comprises the statistical aspect of the scheme, yielding a modification to the HATRACK portion of the forecast.

Renard and Levings (1969) presented applications of the forecasting technique to the 1967 tropical cyclones of the North Atlantic and Western North Pacific Oceans. Daley (1969) tested variations of the scheme, and included an analysis of the 1968 tropical cyclone data. A significant improvement to the modification component of the forecast was reported on by Renard, Daley, and Rinard (1970). The forecast scheme in its present form is known as MODIFIED HATRACK (MODHATR).

## II. OBJECTIVES OF THE STUDY

The objectives of the study were as follows:

(1) To compile MODHATR error statistics for the 1969 and 1970 North Atlantic hurricane seasons.

(2) To compare those MODHATR error statistics with data from earlier years and with other forecast schemes.

(3) To explore possible areas of improvement to the MODHATR scheme by:

a) placing the previously-derived empirical limits, used in the modification component, on a firm statistical basis,

b) devising a technique for objective selection of the optimum steering level and mode,

c) comparing the error statistics for forecasts initiated from synoptic-time and warning-time positions.

## III. THE MODIFIED HATRACK SCHEME

As stated in section I, a MODIFIED HATRACK (MODHATR) forecast consists of two parts, one numerical (the HATRACK steering component), and one statistical (the modification component).

### A. THE NUMERICAL HATRACK STEERING PROGRAM

The HATRACK component is based on the assumption that at some level the geostrophic wind, as derived from the FNWC's SR field, can be used as a steering current for the tropical cyclone center. This technique was first introduced by Renard (1968), where it is described in detail.

An SR field results from a numerical program which performs a smoothing operation on an isobaric height field, the amount of smoothing being somewhat dependent on the amplitude and wavelength of the original pattern. The SR field portrays long-wave patterns of the original height field with most disturbance-scale features, including tropical cyclones, filtered out. Point values of geostrophic SR wind at a storm center are computed and used to steer the tropical cyclone. Although SR fields at several levels are available, only the 700 mb level is presently used to generate the HATRACK portion of the MODHATR forecast. Both the SR analysis and attendant prognostic fields, at six-hour intervals to 48 hours, are used to derive the HATRACK positions.

An example of a HATRACK forecast set is given in Fig. 1. A HATRACK forecast set is defined as a series of forecast tropical cyclone positions at six-hour intervals from a given starting time. In Fig. 1, 0600 GMT, 15 September 1970 (06150970) is the starting time and date and 26.6° N, 87.3° W is the initial position of tropical storm Felice. In this example, forecast positions are given only to the 66-hour interval (00180970); whereas, HATRACK forecasts usually are computed to 72 hours. 00150970 indicates the time and date of the SR analysis and its attendant prognoses used to derive the geostrophic steering component. The number in the last column indicates the forecast motion for a six-hour period centered at the date/time given at left.

B. THE MODIFICATION COMPONENT

When the forecast tracks dependent on HATRACK steering only were compared with best track positions[1] of many tropical cyclones, it was noted that the forecast and actual tracks were frequently similar in shape, but out of phase with respect to time. The HATRACK forecasts exhibited this sort of bias (a deficiency in both zonal and meridional components) in a majority of the tracks studied. Such bias, if known and consistent in time, can be used to correct the numerical steering component, and results in a MODHATR forecast which is more accurate than the HATRACK component alone.

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[1] Best track positions refer to the documentary locations of the cyclone centers.

This modification technique is described below. Daley (1969) describes it more completely.

The MODHATR scheme employs a linear extrapolation of the known HATRACK errors at short forecast intervals (six and twelve hours) to correct MODHATR forecasts for longer periods of up to 72 hours. The application is carried out for the latitudinal and longitudinal components separately, with certain restrictions on the size of the correction that is generated. The assumption is made that whatever circumstances combined to cause an error early in the forecast period will continue to act in a like manner during the later part of the forecast period.

To produce a MODHATR forecast to "X" hours, HATRACK positions to "X+12" hours must have been computed, and the position of the storm at the six- and twelve-hour intervals of the HATRACK forecast must be known. The following formula is used to linearly extrapolate these known six- and twelve-hour HATRACK forecast errors (E) to any interval, $\Delta t_n$, with time, in hours, represented by $t_n$:

$$E_{\Delta t_n} = E_{12} + [(E_{12} - E_6)(t_n - 12)] / 6 \qquad (1)$$

Thus, the estimated error at 24 hours is simply the error at 12 hours plus twice the difference between the error at twelve and six hours. These extrapolated errors are then applied as corrections to the HATRACK positions to obtain a MODHATR position by using the formula

$$F'_{t_n-12} = F_{t_n} + E_{\Delta t_n}, \qquad (2)$$

where $F'_{t_n-12}$ is the MODHATR forecast for an interval 12 hours less than $t_n$, and $F_{t_n}$ is the HATRACK position for time $t_n$.

Fig. 2 illustrates graphically how the HATRACK track is modified to produce a MODHATR forecast. This is a simplified hypothetical example. Note how the vector error generated in the first 12 hours of the HATRACK forecast is used to correct the later HATRACK positions in the forecast set.

A worksheet (Fig. 3) has been developed to aid in the manual calculation of the modification component. In the example, HATRACK positions from the output reproduced in Fig. 1 have been used with best track data for the six- and twelve-hour intervals to provide a MODHATR forecast set to the 48-hour forecast interval. It should be noted that applying the modification shortens the effective forecast period by 12 hours, as in the case cited, from 60 to 48 hours. For the 1971 season, HATRACK is being computed to 84 hours. This allows a 72-hour MODHATR forecast to be generated for the first time.

There are four special empirical rules listed at the bottom of the worksheet. The purpose of these rules is to limit the amount of correction that can be applied to HATRACK by the modification scheme. The limits on the error correction are necessary to prevent large and unrepresentative errors in the six- and twelve-hour HATRACK positions from causing a projection of excessive corrections at later intervals. Note that in this example, special rule number 4

was applied causing a limit to be placed on the amount of correction applied to the $F'_{36}$ longitude component and the F'48 latitude and longitude components.

Fig. 4 shows a plot of the best track, HATRACK, and MODHATR positions for the sample case presented in Figs. 1 and 3.

## IV. TESTING PROCEDURES

### A. DATA SOURCES

The HATRACK steering components for the 1969 and 1970 Atlantic hurricane seasons were computed on a real-time basis by FNWC, Monterey, for research purposes, and by Fleet Weather Central (FWC), Norfolk, for operational use by Fleet Weather Facility (FWF), Jacksonville. Data were available for all 1969 storms and all 1970 storms except Dorothy. The best track data used to compute the modification portion of the MODHATR forecasts and derive error statistics were provided by FWF, Jacksonville.

MODHATR forecasts and statistics were computed using research-oriented computer programs written in FORTRAN IV language and run on the Naval Postgraduate School's IBM 360-67 computer.

### B. 1970 DATA PECULIARITIES

An irregularity was inadvertantly included in the computations of the HATRACK steering component for the last three storms of the 1970 season. All forecasts were initiated from warning-time positions (1000, 1600, 2200, and 0400 GMT); however, these positions were assigned to the synoptic time equivalent to warning time plus two hours (1200, 1800, 0000, and 0600 GMT), and the forecasts printed out for six-hour intervals from then on through the forecast set. For example, if a warning-time message indicated a storm position of

24.5° N, 95.3° W at 1600 GMT, the HATRACK forecast was initiated from that position but at the closest synoptic time (1800 GMT). In order to provide valid comparisons, best track data were interpolated so that in the above example, the 0600 GMT HATRACK position (actually a 0400 GMT position) is compared with a 0400 GMT best track position, and so on through the forecast intervals of the forecast set.

An additional difference in some of the 1970 data from that of other years arises from the introduction of the primitive equation model at FNWC on 1 September 1970. From that point on, most of the pronostic height fields used to derive geostrophic SR winds, from which the HATRACK positions are computed, were obtained from the primitive equation model.

As will be shown in section V, neither of these peculiarities of the 1970 data appeared to significantly influence the overall results for 1970 as opposed to other years.

## C. ERROR COMPUTATIONS

Error is defined as the total vector difference between MODHATR forecast positions and corresponding best track positions of the tropical cyclone center, expressed as actual minus forecast position. All error computations were made in terms of latitude and longitude components and the magnitude of total error. Unless otherwise stated, all errors presented in the tables and graphs are total vector errors expressed in nautical miles per hour of forecast interval. Thus, the total error of 120 nautical miles for a 24-hour period is expressed as an error of 5.0 knots. Expressing

errors in this way allows for easy comparison of forecasts of slightly varying lengths and facilitates the grouping of forecast intervals.

It should be noted that best track rather than operational positions have been used to compute the modification component. Since error statistics are derived from a comparison with best track data, results may be biased in favor of the MODHATR scheme depending on the amount that operational differ from best track positions. 1971 forecasts are being prepared on a real-time basis using operational data to derive the modification component.

## D. OTHER FORECAST METHODS USED IN THE COMPARISON STUDY

OFFICIAL forecasts subjectively derived jointly by FWF, Jacksonville, and NHC, Miami, in real time were generated from warning-time positions for 8, 20, 44, and 68 hour forecast intervals.

NHC-67 is a statistical prediction method developed by the National Hurricane Research Center, Miami, Florida. It employs regression equations which include many predictors, including pressure changes at various heights and grid points, geostrophic wind components, and past movement, among others. NHC-67 data were supplied by NHC, Miami. The forecasts were generated at synoptic times. Miller, Hill, and Chase (1968) give a more complete description of the technique.

TYRACK, developed by Fleet Weather Central, Pearl Harbor, is a scheme similar to HATRACK (and originally derived from

from it), using smoothed tropical wind fields to generate steering winds at various levels. The level with the lowest vector error in earlier forecasts is chosen as the best steering level. If such forecast history is unavailable, the 700 mb level is chosen. TYRACK data for 1970 were provided by FWC, Norfolk, as run operationally for FWF, Jacksonville.

## V. MODIFIED HATRACK ERROR ANALYSES FOR THE 1969 AND 1970 ATLANTIC HURRICANE SEASONS

### A. 1969 and 1970 TROPICAL CYCLONE TRACKS

1969 was a year of very high tropical cyclone activity in the North Atlantic Ocean. As can be seen from Fig. 5, it was also a difficult year for hurricane forecasters, with six of the thirteen named cyclones exhibiting very erratic behavior. Camille was the most noteworthy storm of the season, a super-hurricane with 190 mph winds responsible for much damage on the Gulf Coast and severe flooding in the Middle-Atlantic states.

Fig. 6 indicates the tracks of the 1970 storms. Nearly all of the tropical cyclones were confined to the Gulf of Mexico. Only one storm, Alma, behaved erratically. Celia, with winds of 160 mph, was the most significant storm of the season.

### B. COMPARISON OF THE 1969 AND 1970 MODHATR ERROR STATISTICS WITH THOSE OF EARLIER YEARS

Fig. 7 contrasts the 1969 and 1970 MODHATR results with those of the 1967 and 1968 seasons. The graph shows forecast error, in nautical miles per hour of forecast interval, as a function of forecast interval, in hours. 1970 ranks as a typical year with errors ranging from 3.5 kt at 12 hours to 5.5 kt at 60 hours. The 1970 data display an error rate increasing with forecast interval, as do 1967 and 1969.

MODHATR performance in 1969 was appreciably worse than any other year in the study, for all forecast intervals. Two possible explanations are offered. First, almost all of the forecasts were generated from warning-time positions which tend to be less accurate than synoptic-time positions (see section VI). Second, as stated earlier, nearly half of the storms exhibited an erratic behavior during part of their life history. This is an indication that weak, nondescript, or rapidly varying steering currents were associated with certain positions of the cyclone track. The latter, in particular, is likely to be associated with non-linear HATRACK errors as a function of time. The modification scheme, based on a linear extrapolation of errors, does not properly handle such cases.

## C. COMPARISONS OF THE ACCURACY OF MODHATR FORECASTS WITH OTHER SCHEMES

### 1. MODHATR vs OFFICIAL Forecasts

Figs. 8 and 9 compare MODHATR results with OFFICIAL forecasts. Fig. 8 indicates the results of a non-homogeneous comparison. In this case, all forecasts for a particular forecast interval are compared without regard to verification times. It should be noted that because OFFICIAL forecasts are initiated at warning times (0400, 1000, 1600, and 2200 GMT), MODHATR forecasts are being compared with OFFICIAL forecasts originating four hours later. The time difference is accounted for by dividing the forecast error by the

appropriate forecast interval to get an error in nautical miles per hour. Comparison is facilitated by forming an error ratio of OFFICIAL error divided by MODHATR error. Thus, an error ratio greater than 1.0 indicates that the MODHATR forecasts are more accurate than OFFICIAL. OFFICIAL forecasts are made for 12-, 24-, 48-, and 72-hour intervals, while MODHATR includes only those intervals to 60 hours; therefore, no 72-hour comparisons are possible. Below the graph are listed ratios indicating the number of OFFICIAL forecasts to the number of MODHATR forecasts for each of the forecast intervals compared. To the right of each ratio, in parenthesis, is the average MODHATR error, in kt, for that time interval and year.

Fig. 9 is similar to Fig. 8 except that it indicates the results of a homogeneous comparison, that is, a comparison of OFFICIAL and MODHATR forecasts of similar time interval verifying at the same time. Below the graph are listed the number of cases involved in the comparison by year, and in parenthesis, the average MODHATR error, in kt.

Both Figs. 8 and 9 indicate a definite superiority of MODHATR over OFFICIAL results in the forecast intervals through 24 hours, which deteriorates to near parity at 48 hours.

2. <u>MODIFIED HATRACK vs NHC-67 Forecasts</u>

Figs. 10 and 11 are of the same format as Figs. 8 and 9, except they compare MODHATR with the NHC-67 scheme described in section IV. Fig. 10 indicates that in a non-homogeneous comparison, MODHATR excels NHC-67 in all years

and forecast intervals except at 36 and 48 hours in 1969. Fig. 11 gives the combined homogeneous comparison for all four years. MODHATR is superior in all forecast intervals, especially through 24 hours. The large number of forecast cases with poor results in 1969 heavily influences the results in Fig. 11.

3. MODIFIED HATRACK vs TYRACK

Fig. 12 indicates that when all forecasts are considered in a non-homogeneous comparison, MODHATR is superior to TYRACK for all forecast intervals, especially to 36 hours. Fig. 13 is of the same form as other homogeneous comparisons, and shows that MODHATR excels TYRACK at all forecast intervals. These figures contain only 1970 data, since TYRACK data are not available for previous years.

# VI. EXPERIMENTS TO IMPROVE THE MODIFIED HATRACK SCHEME

## A. TESTS TO DETERMINE EMPIRICAL LIMITS TO THE MODIFICATION PROCEDURE

The worksheet developed to aid in the hand computation of the modification portion of the MODHATR forecast was included as Fig. 3. Four special rules developed to enhance the performance of the modification scheme are listed at the bottom of Fig. 3. The first allows only small modifications to be made to the HATRACK forecast if the error at the 12-hour time interval is zero. The other three special rules, whose development is described by Daley (1969) and Renard, Daley and Rinard (1970), were also designed to limit the amount and type of error correction made by the modification. These rules help prevent large or unrepresentative errors at the six- and twelve-hour HATRACK positions from causing very large corrections to be applied to later forecast positions when the early errors are linearly extrapolated. Although these rules may be explained from their utilization on the worksheet, it is much simpler to understand their function and effect if the linear extrapolation of errors is presented graphically rather than algebraically.

Fig. 14 is a diagram for graphically computing the forecast relative HATRACK error as a function of the forecast interval. Relative HATRACK error is defined as the ratio of the error for any $\Delta t$-hour interval to the error at the

12-hour interval. At the 12-hour interval, the error for both the six- and twelve-hour HATRACK positions is assumed to be known, and the six-hour relative HATRACK error ratio can be computed and plotted. The 12-hour relative HATRACK error ratio is always 1.0 by definition. From these two points on the graph, the relative HATRACK error can be linearly projected for any time interval desired. For example, in Fig. 14, the plotted six-hour relative HATRACK error for longitude is 1.5 and the 12-hour relative error is 1.0. These result in linearly extrapolated relative errors of 0.0 at 24 hours and -1.0 at 36 hours, etc. The relative HATRACK error for any particular forecast interval is then multiplied by the 12-hour error to obtain the modification to be applied to the HATRACK position. A more detailed explanation of Fig. 14 is given by Daley (1969).

If no restriction were placed on the generated relative error curves, very large six-hour relative errors would result in the production of unreasonably large corrections at longer forecast intervals, as stated earlier. For this reason, two of the special rules limit six-hour relative HATRACK error values to the range +0.5 to +2.0. That is, if the relative error at six hours were algebraically less than +0.5, it would be set at +0.5, and if it were greater than +2.0, it would be set at +2.0. Values between +2.0 and +0.5 would remain unchanged. In addition, the largest value of relative error allowed to be generated has been limited to ±3.0 by another of the special rules.

By adapting these limits to the relative HATRACK error, the extrapolated relative error curves were allowed to range only in the checked area of the graph in Fig. 14. The limits on relative error at time intervals of less than 36 hours were determined by the limits on the six-hour relative error (+2.0, +0.5), whereas, the overall limits of ±3.0 influence the maximum relative error allowed at time intervals equal to or greater than 36 hours.

A different combination of limits will allow a different range of relative errors to be computed. For example, if +0.8 and +1.2 are used at the six-hour interval as limits on the relative error, computed relative error values would be restricted to include only the enclosed clear area of Fig. 15, eliminating the hatched area that would be allowed if +0.5 and +2.0 were used as the six-hour limits as in Fig. 14. Various other combinations would allow different values of computed relative HATRACK error to be generated by the modification scheme.

An experiment was conducted using data from 1967, 1968, and 1970 to determine the optimum choice of relative error limits since the presently used combination of ±3.0 (overall) and +2.0, +0.5 (at six hours) was chosen without a thorough investigation into the performance of other possible combinations. The average error per hour of forecast interval for each of 11 sets of limits is shown in Table 1. The results were obtained by running the bias correction program with each of the sets of limits for each available HATRACK

forecast set, and averaging the resulting errors. The number of forecasts for which the average error applies is listed in parentheses adjacent to the forecast interval at the top of the table. Overall limits are listed first, then six-hour limits. Thus, $\pm 3.0 \begin{smallmatrix} +2.0 \\ -6.0 \end{smallmatrix}$ in the limit combination column implies that ±3.0 are the overall limits, and +2.0 and -6.0 are the six-hour relative error limits used to derive the listed error values. The combination presently used in the MODHATR scheme is listed as number 10 (illustrated in Fig. 14). Combination number eight is the one illustrated in Fig. 15.

Table II combines the three-year sample listed in Table 1 into an overall evaluation for each combination of the HATRACK relative error limits. It can be seen that combination number 10, the combination already in use, provides error values as low as, or lower than any of the other tested values. As might be expected, if larger relative error values are allowed to be generated, as in combination number 11, the performance of the MODHATR scheme deteriorates.

It should be noted that changes in the empirical limits used do not influence the average error for the scheme to a very great degree unless the limits are drastically changed.

## B. AN EXPERIMENT TO DEVELOP A LEVEL- AND MODE-SELECTION TECHNIQUE

Although the MODHATR forecasts based on SR steering winds from 700 mb analyses and prognoses constitute the present scheme, variations in level and basic fields are

possible. Past research has indicated that on occasion (but not on the average) 1000 mb or 500 mb SR winds yield more accurate steering than 700 mb SR winds, and that winds derived from a single SR analysis only (anal-mode), dated near initiation time of the forecast, vice winds from SR analysis and prognoses (prog-mode) may, at times, also produce more accurate steering.

With these thoughts in mind, two hypotheses were tested. (1) On the average, if a HATRACK forecast at a particular level and for a certain mode displayed a smaller error than other levels and modes for the 12-hour forecast interval, then it would continue to show smaller errors throughout a forecast set. (2) The HATRACK forecasts chosen in this way would produce better MODHATR forecasts than the presently structured scheme.

To investigate hypothesis (1), data from 1967, 1968, and 1970 were used. For the investigation into the validity of hypothesis (2), data from six storms of the 1970 season were used. Prog- and anal-mode HATRACKS were available for the first three 1970 storms; however, only the prog-mode was available for the last three. This is not a particularly important consideration because the major differences in the forecast positions lie among the levels rather than modes used, and all three levels were available in all cases.

The results of the investigation are shown in Tables III and IV, with the number of cases included in parenthesis adjacent to the forecast interval. In Table III, 700 mb prog

refers to the 700 mb prog-mode performance at the various time intervals. Again, this is the steering component presently used in the MODHATR scheme. Best level/mode refers to the level and mode which displayed the lowest error figures at the 12-hour interval for each forecast set. Percent improvement indicates the percentage improvement found in average HATRACK statistics of the best level/mode as opposed to the 700 mb prog-mode averages. The data summarized in Table III indicates that hypothesis (1) is valid. The best level/mode HATRACK forecasts produce results which, on the average, are superior to the 700 mb prog-mode HATRACK forecasts at all intervals, in all three years tested. The advantage decreases with increasing forecast interval.

Table IV, relating to hypothesis (2), is arranged in the same manner as Table III, except that 1970 data only are included, and the results pertain to the MODHATR forecasts that are derived from the best level/mode and the 700 mb prog-mode steering components whose average errors appear in Table III. The results listed in Table IV are rather unexpected. They indicate that even though the best-level/mode HATRACK forecasts are more accurate, on the average, than the 700 mb prog-mode HATRACKS, the latter produce much better MODHATR forecasts. This is the antithesis of hypothesis (2) discussed earlier. The percent loss figures refer to the percentage loss in accuracy realized if the best-level/mode MODHATRS are used rather than the 700 mb prog-mode MODHATRS.

This result was so contrary to what was expected that several of the cases that exhibited the largest loss in accuracy were plotted as an aid in diagnosing the cause of the poor performance of the level/mode-selection scheme.

Fig. 16 is typical of the cases plotted. Point Z represents the 0600 GMT position of tropical storm FELICE on 17 September 1970 (i.e., 1617). $Y_1$ represents the 700 mb prog-mode HATRACK position as forecast for 0600 GMT (a 48-hour forecast). $X_1$ is the best-level/mode (1000 mb prog-mode) 48-hour HATRACK forecast position for 0600 GMT. Note that the best-level/mode HATRACK represents an excellent forecast of the storm movement, whereas, the 700 mb steering is rather poor.

When the modification is applied, the picture is changed considerably. The previously poor 700 mb prog-mode HATRACK position, $Y_1$, is modified to point $Y_2$, quite close to the 0600 GMT position of the storm. However, the excellent best-level/mode HATRACK, $X_1$, is modified to point $X_2$, almost seven degrees west of the storm's position at Z. This sort of phenomenon occurred often enough to cause best-level/mode MODHATRS to have an average error greater than the best-level/mode MODHATRS themselves, while the 700 mb prog-mode HATRACKS were greatly improved by the modification.

These figures indicate that perhaps the best-level/mode steering forecasts were being modified by too large a factor, in effect, being moved away from the desired position by the modification. To test this theory, the best-level/mode

HATRACKS were modified by a scheme using +0.8 and +1.2 as six-hour relative error limits, and +2.0 and -1.0 as overall relative error limits. The results are noted in the reduced limits section of Table IV. There is an improvement, but the level/mode-selection scheme still exhibits large errors when compared to 700 mb prog-mode MODHATR forecasts.

A comparison of 1970 data between Tables III and IV indicates that at later forecast intervals, the results of the best-level/mode HATRACK scheme compare very favorably with the present version of MODHATR. Note that in a nonhomogeneous comparison, 48-hour best-level/mode HATRACK errors average 4.0 kt (Table III), while the MODHATR average error was 4.9 kt (Table IV). In addition, the 5.0 kt average error for the 72 hour best-level/mode HATRACK forecasts is identical to the average error for the shorter 60-hour interval of the 700 mb prog-mode MODHATR scheme. If used operationally, however, the 24-hour forecasts of Table III would become 12-hour forecasts, the 48-hour forecasts would be 36-hour forecasts, etc. When this consideration is taken into account, the best-level/mode HATRACK results are no longer superior to 700 mb prog-mode MODHATR forecasts.

## C. COMPARISON OF WARNING-TIME AND SYNOPTIC-TIME INITIAL POSITION ERRORS

Table V shows the results of a test to determine the relative accuracy of tropical cyclone positions determined at warning times (04, 10, 16, 22 GMT) and synoptic times (00, 06, 12, 18 GMT). Latitudinal and longitudinal

components are considered separately for the 1967 through 1970 North Atlantic hurricane seasons.

As can be seen from the table, synoptic-time positions are more accurate than warning-time positions except for the 1968 season. Overall averages indicate that synoptic-time positioning displays much less average error than warning-time positioning. These results might be expected because synoptic-time positions are frequently based on weather reconnaissance fixes near that time, whereas, warning-time positions are often four-hour extrapolations of (near) synoptic-time fixes.

The results of this test indicate that to reduce that part of the forecast error due to incorrect positioning of the center of the tropical cyclone, forecasts should be initiated at synoptic rather than warning times.

## VII. CONCLUDING REMARKS

The following conclusions have been drawn from this investigation:

(1) The MODHATR scheme excels OFFICIAL, NHC-67, and TYRACK forecasts in accuracy in the forecast intervals to 48 hours for all years tested. MODHATR is also superior at the 48-hour forecast interval in 1967 and 1968. At the the 48-hour interval in 1969 and 1970, all schemes tested achieve nearly identical results.

(2) The previously derived empirical limits on relative HATRACK error produced results as good as or better than any other tested combination, and should be retained.

(3) The small differences in error statistics between most combinations of relative HATRACK error limits indicate that the chance of significantly improving the scheme through more complex limit variations is small.

(4) Although the level- and mode-selection technique investigated was not successful, the best-level and-mode HATRACK results show a superiority in later forecast intervals over MODHATR in a non-homogeneous comparison of 1970 data. However, because of the manner in which the best-level and-mode is chosen this superiority would be lost under operational conditions.

(5) The fact that more accurate forecasts do exist, on a case by case basis, as compared to the 700 mb prog-mode forecasts indicates that efforts to investigate level-and mode-selection methods should continue.

(6) To reduce errors in the initial position of tropical cyclones, forecasts should be initiated at synoptic times rather than warning times.

| NO. | LIMIT COMBINATION | | 1967 12hr (53) | 1967 24hr (52) | 1967 48hr (45) | 1967 60hr (18) | 1968 12hr (58) | 1968 24hr (51) | 1968 48hr (40) | 1968 60hr ( 2) | 1970 12hr (44) | 1970 24hr (38) | 1970 48hr (25) | 1970 60hr (14) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ±3.0 | +2.0 -6.0 | 3.3 | 3.6 | 4.4 | 4.8 | 3.6 | 4.6 | 4.9 | 4.2 | 3.7 | 4.1 | 5.1 | 5.7 |
| 2 | ±3.0 | +6.0 +0.5 | 3.1 | 3.6 | 4.4 | 4.8 | 3.7 | 4.6 | 4.9 | 4.2 | 3.4 | 4.1 | 5.1 | 5.7 |
| 3 | ±3.0 | ±6.0 | 3.3 | 3.6 | 4.4 | 4.8 | 3.6 | 4.6 | 4.9 | 4.2 | 3.7 | 4.1 | 5.1 | 5.7 |
| 4 | ±100.0 | +2.0 +0.5 | 3.1 | 3.6 | 4.6 | 5.1 | 3.7 | 4.6 | 5.5 | 6.7 | 3.4 | 4.1 | 5.6 | 6.4 |
| 5 | ±5.0 | +2.0 +0.5 | 3.1 | 3.6 | 4.6 | 4.9 | 3.7 | 4.6 | 5.5 | 6.0 | 3.4 | 4.1 | 5.6 | 6.3 |
| 6 | +5.0 -1.0 | +2.0 +.25 | 3.1 | 3.8 | 4.6 | 4.9 | 3.6 | 4.8 | 5.5 | 6.0 | 3.4 | 4.1 | 5.6 | 6.3 |
| 7 | +2.0 -1.0 | +1.5 +.75 | 3.5 | 3.8 | 4.7 | 5.0 | 4.6 | 4.9 | 4.8 | 3.3 | 3.4 | 3.9 | 5.0 | 5.0 |
| 8 | ±3.0 | +1.2 +0.8 | 3.7 | 4.0 | 4.5 | 4.8 | 4.9 | 5.0 | 4.8 | 4.2 | 3.6 | 4.1 | 4.9 | 5.7 |
| 9 | +2.0 -1.0 | +1.5 +0.5 | 3.1 | 3.8 | 4.7 | 5.0 | 3.7 | 4.9 | 4.8 | 3.3 | 3.4 | 3.9 | 5.0 | 5.9 |
| 10 | ±3.0 | +2.0 +0.5 | 3.1 | 3.6 | 4.4 | 4.8 | 3.7 | 4.6 | 4.9 | 4.2 | 3.4 | 4.1 | 5.1 | 5.7 |
| 11 | ±100.0 | ±6.0 | 3.8 | 4.5 | 5.5 | 6.1 | 3.5 | 4.7 | 5.7 | 6.9 | 4.0 | 4.7 | 6.3 | 6.3 |

Table I. Table shows average error (in kt) for various forecast intervals of 11 combinations of relative HATRACK error limits for the 1967, 1968, and 1970 North Atlantic hurricane seasons. The limit combination column indicates overall limits, (as ±3.0) and limits on six-hour relative HATRACK errors as +2.0. The number of cases used to derive the average error statistics is listed in parenthesis below the forecast interval.

| NO. | LIMIT COMBINATION | | 12hr (155) | 24hr (141) | 48hr (110) | 60hr (34) |
|---|---|---|---|---|---|---|
| 1 | ±3.0 | +2.0<br>-6.0 | 3.6 | 4.1 | 4.7 | 5.1 |
| 2 | ±3.0 | +6.0<br>+0.5 | 3.4 | 4.1 | 4.7 | 5.1 |
| 3 | ±3.0 | +6.0<br>-6.0 | 3.5 | 4.1 | 4.7 | 5.1 |
| 4 | ±100.0 | +2.0<br>+0.5 | 3.4 | 4.1 | 5.1 | 5.8 |
| 5 | ±5.0 | +2.0<br>+0.5 | 3.4 | 4.1 | 5.1 | 5.6 |
| 6 | +5.0<br>-1.0 | +2.0<br>+.25 | 3.4 | 4.2 | 5.1 | 5.6 |
| 7 | +2.0<br>-1.0 | +1.5<br>+.75 | 3.9 | 4.2 | 4.8 | 5.2 |
| 8 | ±3.0 | +1.2<br>+0.8 | 4.1 | 4.4 | 4.7 | 5.1 |
| 9 | +2.0<br>-1.0 | +1.5<br>+0.5 | 3.4 | 4.2 | 4.8 | 5.2 |
| 10 | ±3.0 | +2.0<br>+0.5 | 3.4 | 4.1 | 4.7 | 5.1 |
| 11 | ±100.0 | ±6.0 | 3.7 | 4.6 | 5.7 | 6.2 |

Table II. Same as Table I, except a composite average for all three seasons, 1967, 1968, and 1970.

| | 1967 | 24hr (80) | 48hr (69) | 72hr (49) |
|---|---|---|---|---|
| Error (kt) | 700 Prog-mode | 6.0 | 5.6 | 5.4 |
| | Best level/mode | 4.3 | 4.7 | 4.8 |
| | Percent Improvement | 28.7 | 15.4 | 10.6 |
| | 1968 | 24hr (53) | 48hr (41) | 72hr (--) |
| Error (kt) | 700 Prog-mode | 7.2 | 5.8 | -- |
| | Best level/mode | 5.7 | 5.4 | -- |
| | Percent Improvement | 20.5 | 6.4 | -- |
| | 1970 | 24hr (35) | 48hr (27) | 72hr (14) |
| Error (kt) | 700 Prog-mode | 6.8 | 5.4 | 5.6 |
| | Best level/mode | 4.0 | 4.0 | 5.0 |
| | Percent Improvement | 41.2 | 24.9 | 9.8 |

Table III. Comparison of best-level/mode HATRACK results to 700 mb prog-mode HATRACK results for 1967, 1968, and 1970 North Atlantic hurricane seasons at 24, 48, and 72 hour forecast intervals. Error figures are averages in nautical miles per hour of forecast interval. The number of cases used to derive the averages are in parenthesis.

| | 1970 | 12hr (35) | 24hr (32) | 36hr (27) | 48hr (22) | 60hr (14) |
|---|---|---|---|---|---|---|
| Error (kt) | 700mb Prog-mode MODHATR | 3.2 | 4.0 | 4.8 | 4.9 | 5.0 |
| Error (kt) | Best level/mode MODHATR | 3.6 | 4.5 | 6.2 | 6.1 | 6.8 |
| | Percent loss | 13.0 | 13.0 | 29.7 | 25.0 | 34.3 |
| | Best level/mode(mod) Reduced limits | 3.7 | -- | 5.6 | -- | 6.6 |

Table IV. Comparison of best-level/mode modified results to 700 mb/ prog-mode MODHATR results for the 1970 North Atlantic hurricane season. Error figures are averages in nautical miles per hour of forecast interval. The number of cases used to derive the averages are in parenthesis

| YEAR | LATITUDE SYNOPTIC TIME | LATITUDE WARNING TIME | LONGITUDE SYNOPTIC TIME | LONGITUDE WARNING TIME |
|---|---|---|---|---|
| 1967 | 14.4 (52) | 21.6 (61) | 14.4 (52) | 27.2 (61) |
| 1968 | 20.5 (77) | 17.3 (9) | 22.3 (77) | 9.3 (9) |
| 1969 | 6.3 (24) | 29.3 (152) | 8.7 (24) | 26.8 (152) |
| 1970 | 23.3 (32) | 24.0 (33) | 32.0 (32) | 42.0 (33) |
| 1967-1970 | 17.4 (185) | 26.3 (255) | 19.9 (185) | 28.2 (255) |

Table V. Comparison of the average error of synoptic-time and warning-time starting positions. Error is the vector difference of the best track and synoptic-time or warning-time position, in nautical miles. Number of cases used to derive the average error figure is in parenthesis.

FM FNWF MONTEREY

TO FWF JACKSONVILLE

TROPICAL CYCLONE STEERING

EXPERIMENTAL PROG

J02 FELI

ANAL TIME 00150970

LEVEL 700 MBS

| | | | |
|---|---|---|---|
| 06150970 | 266N | 0873W | 3108 |
| 12150970 | 272N | 0879W | 3206 |
| 18150970 | 278N | 0885W | 3208 |
| 00160970 | 285N | 0891W | 3308 |
| 06160970 | 292N | 0895W | 3306 |
| 12160970 | 298N | 0899W | 3306 |
| 18160970 | 305N | 0903W | 3406 |
| 00170970 | 312N | 0905W | 3506 |
| 06170970 | 318N | 0906W | 3606 |
| 12170970 | 325N | 0906W | 0106 |
| 18170970 | 331N | 0905W | 0106 |
| 00180970 | 337N | 0903W | 0206 |

Fig. 1 Sample HATRACK forecast computer printout. The initial position of tropical storm Felice was 26.6°N 87.3°W at 0600 GMT 15 September 1970. HATRACK forecasts are listed at six-hour intervals to 66 hours in this example.

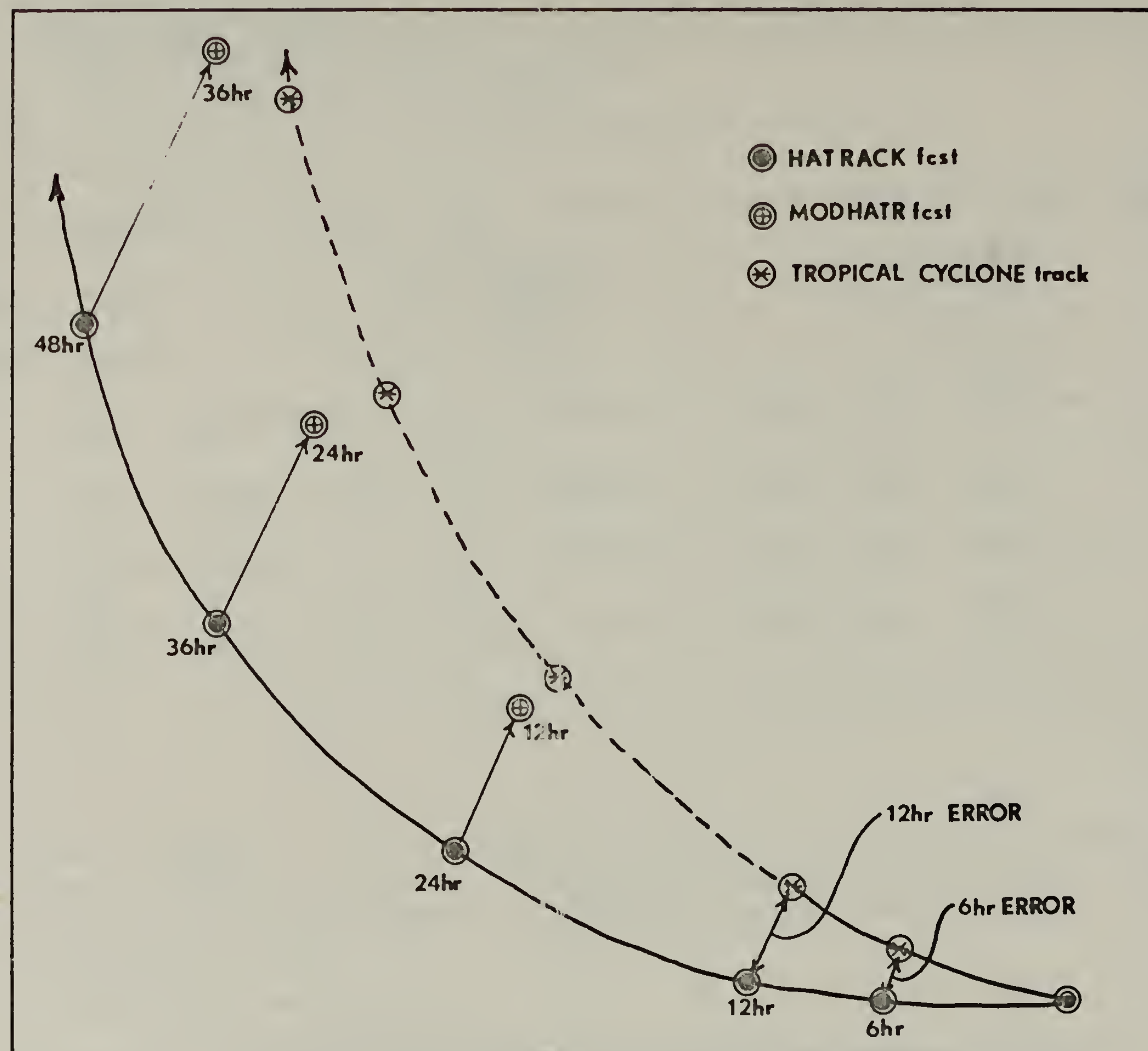



Fig. 2 A simplified hypothetical example of the application of the modification component to a HATRACK forecast. The six- and twelve-hour storm positions are known and used to generate corrections at later intervals.

Basic Formulae: $E_{\Delta t_n} = E_{\Delta t_2} + [(E_{\Delta t_2} - E_{\Delta t_1})(t_n - t_2)]/6$ $\qquad F'_{t_n - t_2} = F_{t_n} + E_{\Delta t_n}$

Legend:
- $F$ = HATRACK forecast position
- $F'$ = MODIFIED HATRACK forecast position
- $E$ = Error in F, computed as true minus forecast position
- $E_{\Delta t_n}$ = Estimated error of F for forecast interval $\Delta t_n$
- $E_{\Delta t_2}$, $E_{\Delta t_1}$ = errors of F for intervals $\Delta t_2$ and $\Delta t_1$, where 5 hr $\le \Delta t_1 \lesssim$ 10 hr and $t_2 - t_1$ = 6 hr
- $t_1$, $t_2$, $t_n$ = time at end of interval $\Delta t_1$, $\Delta t_2$, $\Delta t_n$

Tropical cyclone ____ (#), FELICE (name), 700 - Prog (level - mode) HATRACK Forecast Initiated from 26.6 87.3 (lat-long) at 0600 (time) Z 1509 19 70 (date)

| | Latitude component | Longitude component |
|---|---|---|
| $t_1$ = 1200 (time) Z 150970 (date) | $a = E_{\Delta t_1}$ = +.5 °lat. * | $a = E_{\Delta t_1}$ = +1.7 °long.* |
| $t_2$ = 1800 (time) Z 150970 (date) | $b = E_{\Delta t_2}$ = +.7 °lat. * | $b = E_{\Delta t_2}$ = +3.0 °long.* |
| | $c$ = b-a = +.2 °lat. | $c$ = b − a = +1.3 °long. |
| $F'_{12}$ at $t_n = t_2$ + 12 hr = 0600 (time) Z 160970 (date): | $F'_{12}$ = 29.2 ($F_{t_n}$) + 1.1 ($E_{\Delta t_n}$ = b+2c) = 30.3 °lat. | $F'_{12}$ = 89.5 ($F_{t_n}$) + 5.6 ($E_{\Delta t_n}$ = b+2c) = 95.1 °long. |
| $F'_{24}$ at $t_n = t_2$ + 24 hr = 1800 (time) Z 160970 (date): | $F'_{24}$ = 30.5 ($F_{t_n}$) + 1.5 ($E_{\Delta t_n}$ = b+4c) = 32.0 °lat. | $F'_{12}$ = 90.3 ($F_{t_n}$) + 8.2 ($E_{\Delta t_n}$ = b+4c) = 98.5 °long. |
| $F'_{36}$ at $t_n = t_2$ + 36 hr = 0600 (time) Z 170970 (date): | $F'_{36}$ = 31.8 ($F_{t_n}$) + 1.9 ($E_{\Delta t_n}$ = b+6c) = 33.7 °lat.$ | $F'_{36}$ = 90.6 ($F_{t_n}$) + 9.0 ($E_{\Delta t_n}$ = b+6c) = 99.6 °long.$ |
| $F'_{48}$ at $t_n = t_2$ + 48 hr = 1800 (time) Z 170970 (date): | $F'_{48}$ = 33.4 ($F_{t_n}$) + 2.1 ($E_{\Delta t_n}$ = b+8c) = 35.2 °lat.$ | $F'_{48}$ = 90.5 ($F_{t_n}$) + 9.0 ($E_{\Delta t_n}$ = b+8c) = 99.5 °long.$ |
| $F'_{72}$ at $t_n = t_2$ + 72 hr = — (time) Z — (date): | $F'_{72}$ = — ($F_{t_n}$) + — ($E_{\Delta t_n}$ = b+12c) = — °lat.$ | $F'_{72}$ = — ($F_{t_n}$) + — ($E_{\Delta t_n}$ = b+12c) = — °long.$ |

SPECIAL RULES:

*(1) For b=0: If a ≥0, set b = +0.1; If a <0, set $b_2$ = −0.1; and, if |a|>0.2, set |a|=0.2

*(2) For a and b with opposite algebraic signs, set a=0.5b

*(3) For a = 0 and b ≠0 or both a and b with same algebraic sign:
If |a|/|b|>2.0, change |a| so that a/b = + 2.0
If |a|/|b|<0.5, change |a| so that a/b = + 0.5

$(4) For $E_{\Delta t_n}/b > +3.0$, change $E_{\Delta t_n}$ so that $E_{\Delta t_n}/b = +3.0$;
For $E_{\Delta t_n}/b < -3.0$, change $|E_{\Delta t_n}|$ so that $E_{\Delta t_n}/b = -3.0$

Fig. 3 Sample worksheet used to manually compute the modification component. In this example, steering component positions from Fig. 1 are used with best track data to produce MODHATR forecasts for tropical storm Felice (1970).

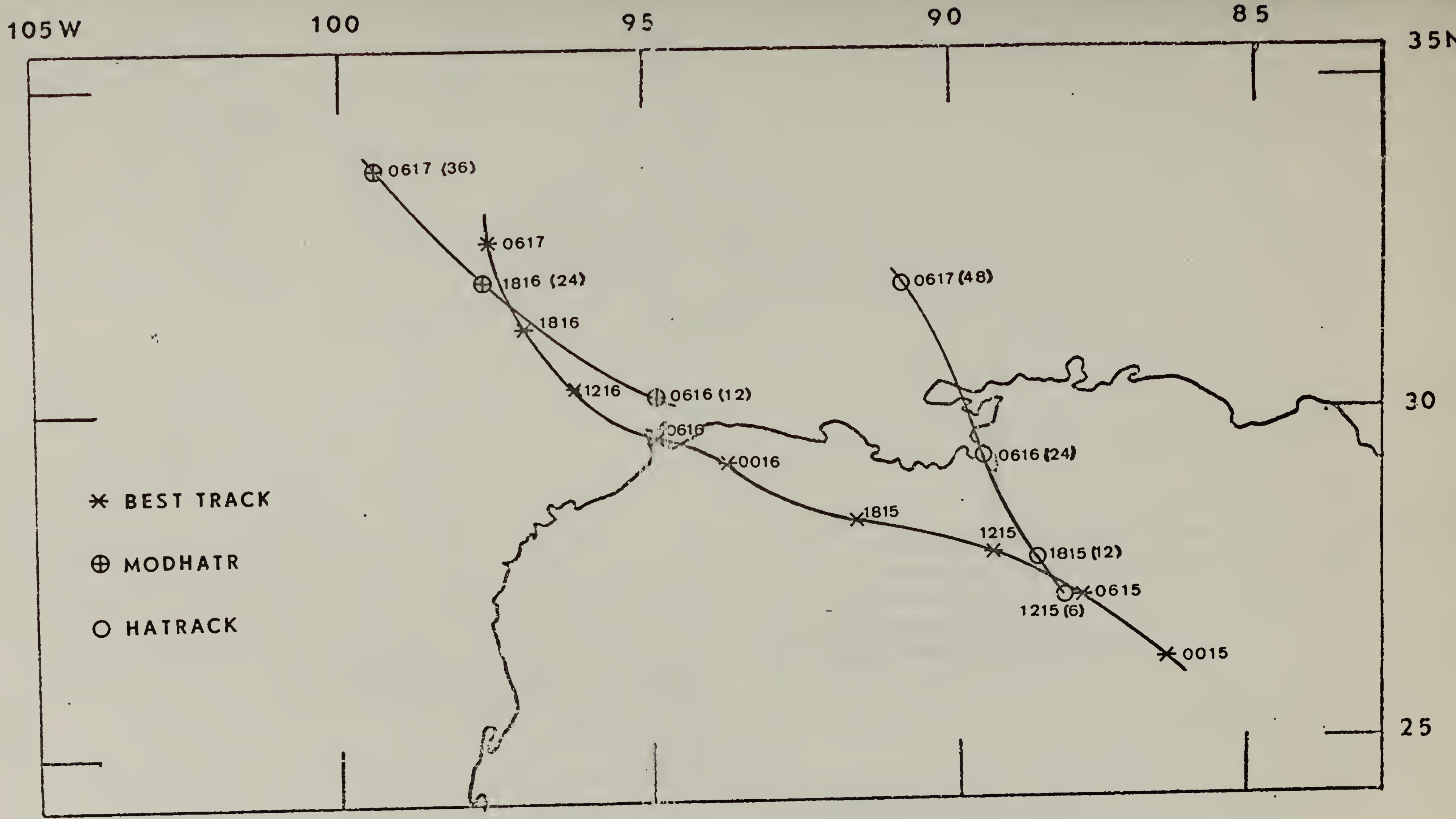



Fig. 4 A plot of the MODHATR, HATRACK, and best track data from Figs. 1 and 3 showing an actual example of the application of the modification component to a HATRACK forecast to derive a MODHATR forecast set.

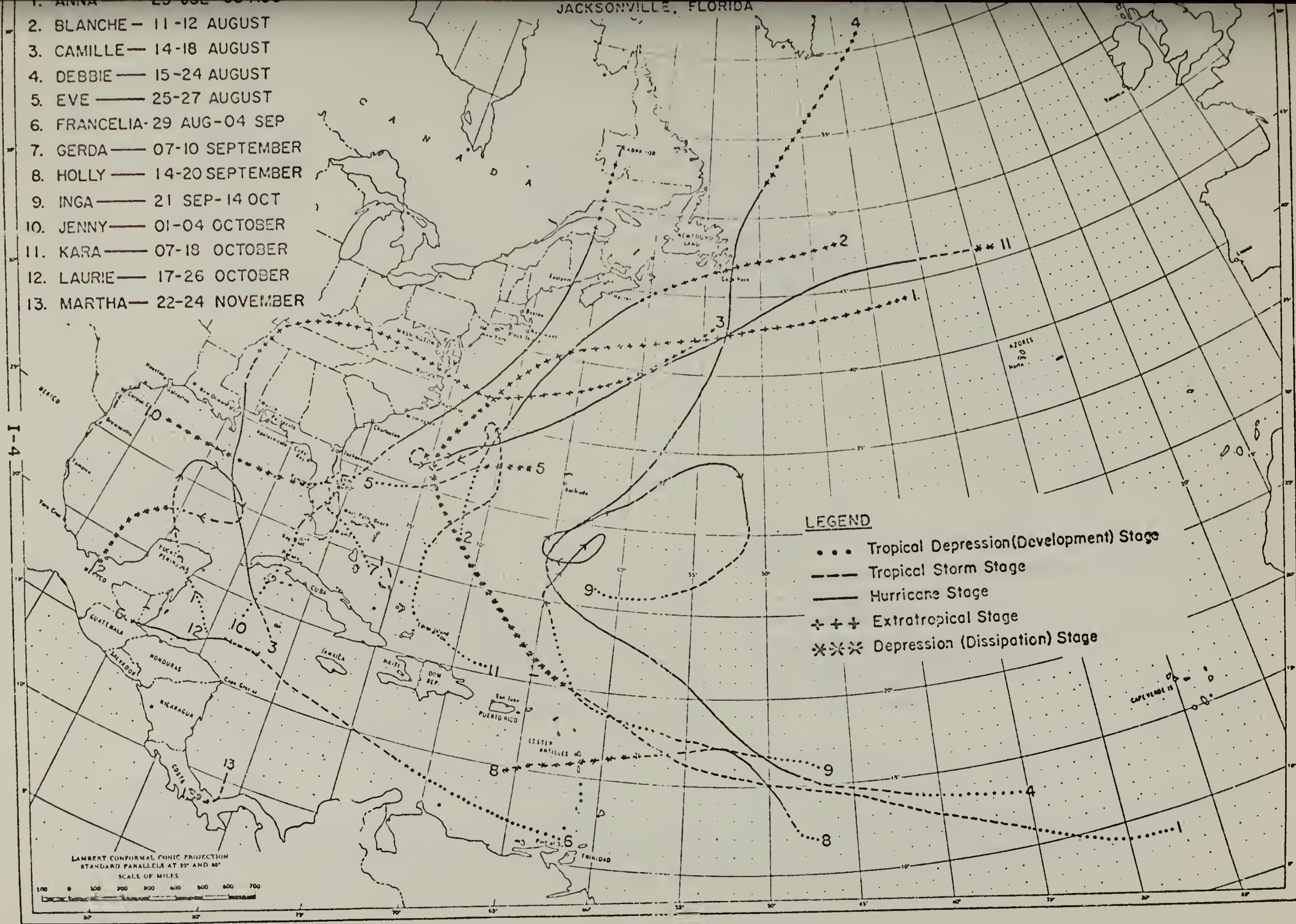



Fig. 5 Tracks of the named tropical cyclones of the 1969 North Atlantic hurricane season as provided by FWF, Jacksonville (1970).

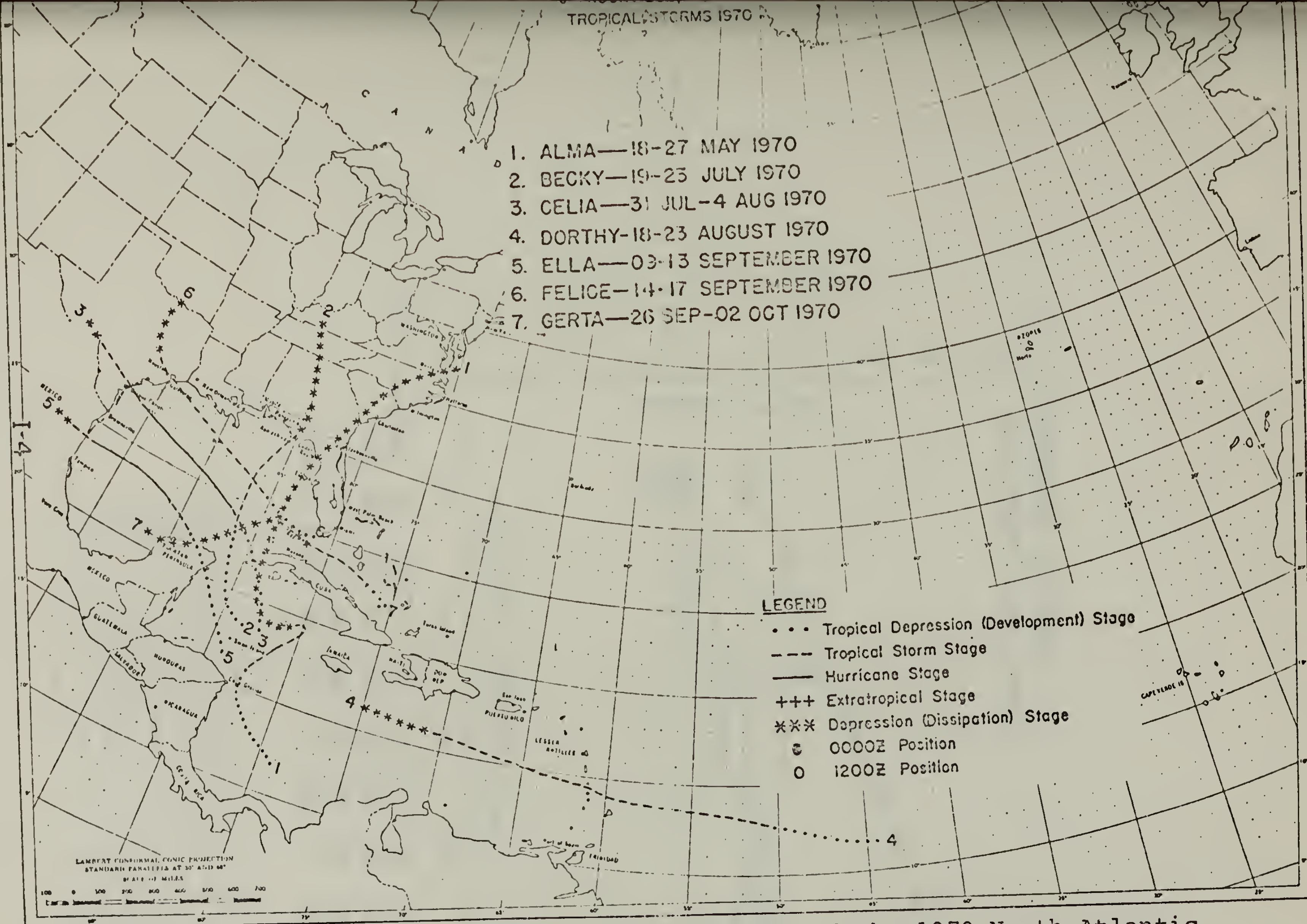
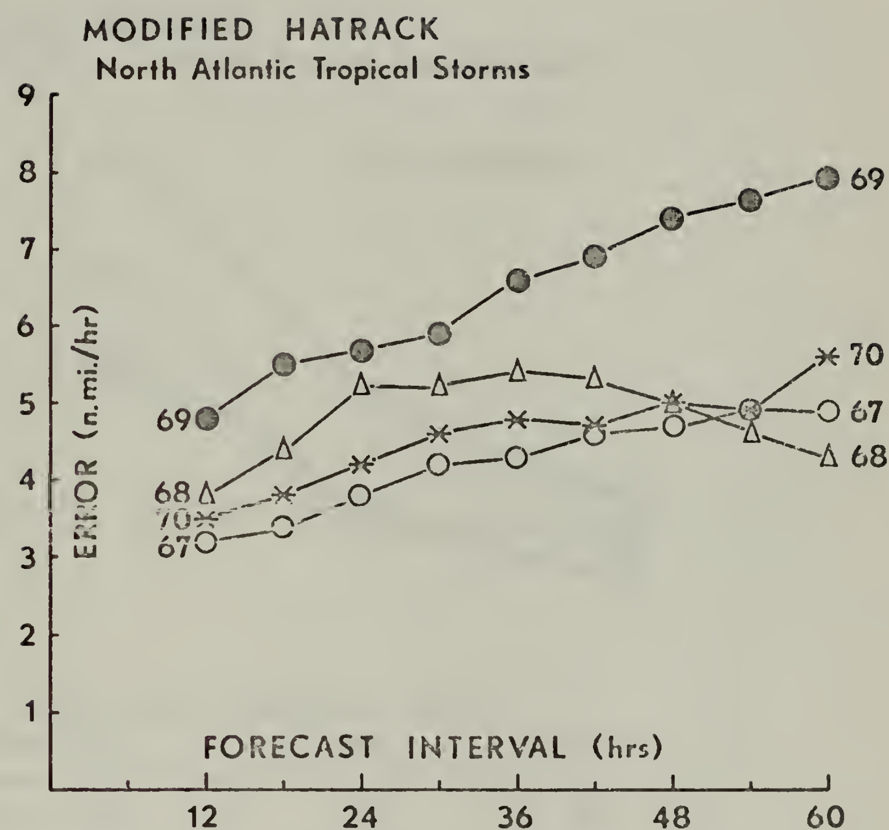
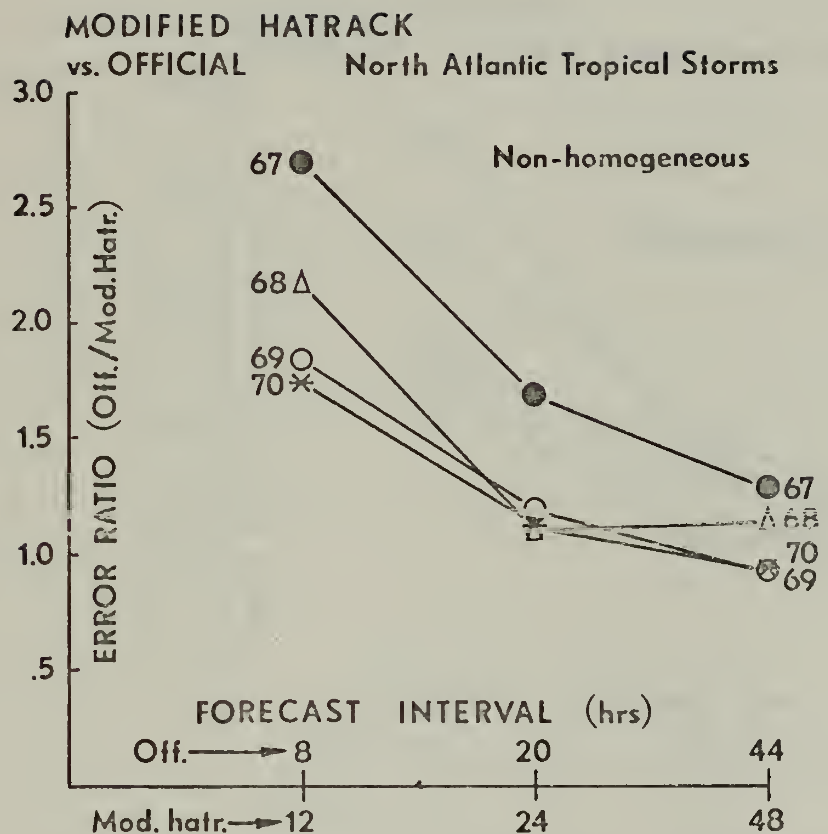



Fig. 6 Tracks of the named tropical cyclones of the 1970 North Atlantic hurricane season as provided by FWF, Jacksonville (1971).



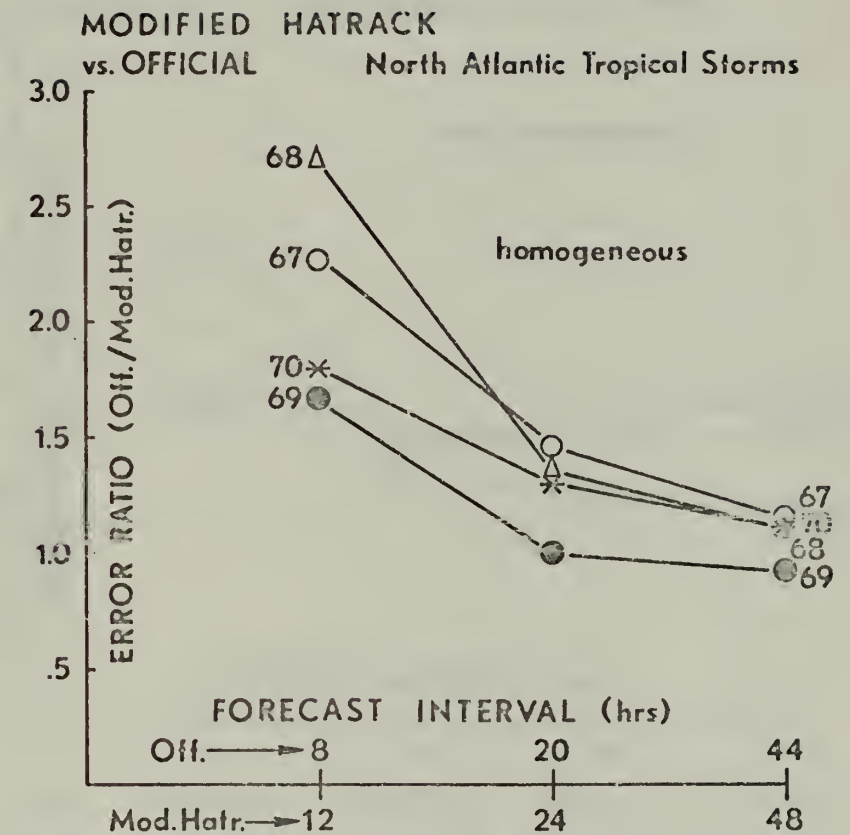

| | 12 | | 24 | | 36 | | 48 | | 60 |
|---|---|---|---|---|---|---|---|---|---|
| No. of fcsts 1967: | 70 | 70 | 67 | 66 | 65 | 61 | 59 | 46 | 25 |
| 68: | 59 | 54 | 51 | 47 | 43 | 41 | 38 | 36 | 2 |
| 69: | 74 | 70 | 64 | 66 | 61 | 57 | 52 | 48 | 2 |
| 70: | 43 | 40 | 37 | 35 | 32 | 28 | 24 | 22 | 14 |

Fig. 7 Plot of average error of MODHATR forecasts in nautical miles per hour as a function of forecast interval, in hours, for the 1967-1970 North Atlantic hurricane seasons. The number of forecasts used to derive the averages is listed below the graph.



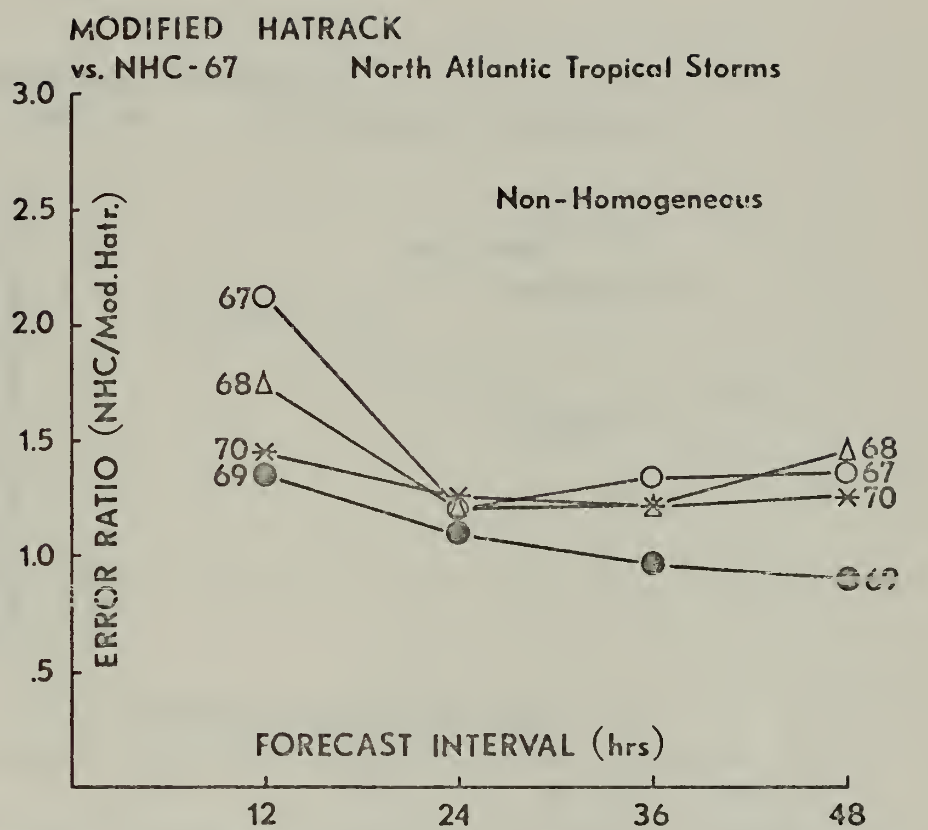

| | | | |
|---|---|---|---|
| 1967: | 215/70(3.2) | 209/67(3.8) | 186/59(4.7) |
| 1968: | 106/59(3.8) | 100/51(5.2) | 78/38(5.0) |
| 1969: | 259/74(4.8) | 240/64(5.7) | 205/52(7.4) |
| 1970: | 62/43(3.5) | 54/37(4.2) | 38/24(5.0) |

Fig. 8 A graph of the error ratio of OFFICIAL/MODHATR forecasts for a non-homogeneous sample as a function of forecast interval for the 1967-1970 North Atlantic hurricane seasons. Listed below is a ratio of the number of OFFICIAL to MODHATR forecasts used to derive the average error figures with the average error of the MODHATR forecasts (in kt) in parenthesis.




| No. fcsts (E./hr) | | | |
|---|---|---|---|
| 1967: | 52(3.3) | 51(3.9) | 47(4.6) |
| 68: | 37(3.6) | 34(4.7) | 25(5.0) |
| 69: | 56(5.0) | 51(6.2) | 39(7.7) |
| 70: | 18(3.6) | 17(3.5) | 11(5.0) |

Fig. 9 Similar to Fig. 8, except a homogeneous comparison of OFFICIAL and MODHATR data.




| | | | | |
|---|---|---|---|---|
| 1967: | 68/70(3.2) | 65/67(3.8) | 62/65(4.3) | 59/59(4.7) |
| 1968: | 42/59(3.8) | 40/51(5.2) | 37/43(5.4) | 35/38(5.0) |
| 1969: | 104/74(4.8) | 87/64(5.7) | 82/61(6.6) | 77/52(7.4) |
| 1970: | 28/43(3.5) | 23/37(4.2) | 20/32(4.8) | 18/24(5.0) |

Fig. 10 Similar to Fig. 8, except a comparison between MODHATR and NHC-67 forecasts.

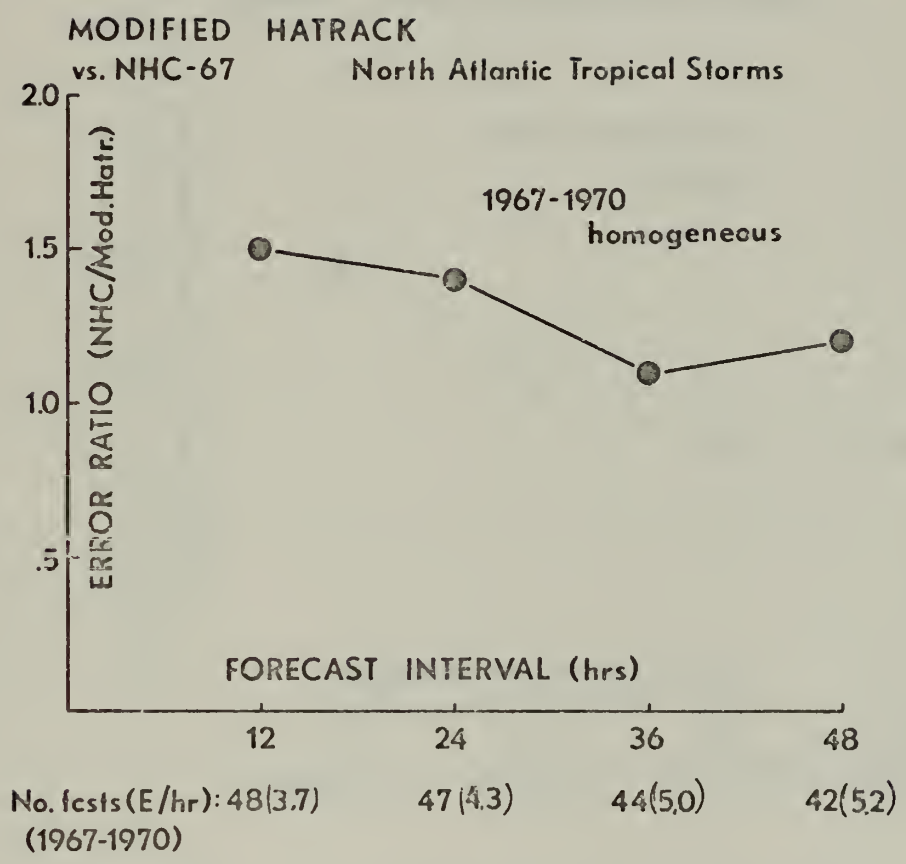



Fig. 11 Similar to Fig. 10, except a homogeneous comparison of MODHATR and NHC-67 for a combination of the 1967-1970 seasons.

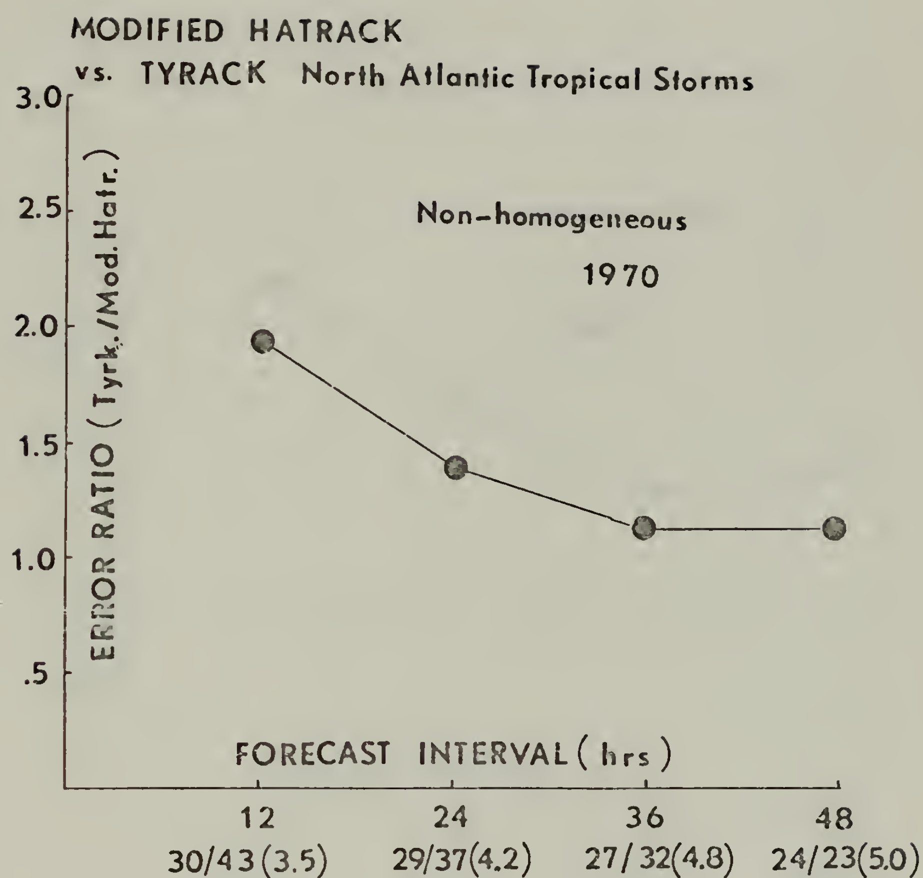



Fig. 12 Similar to Fig. 8 except a comparison between MODHATR and TYRACK for the 1970 season only.

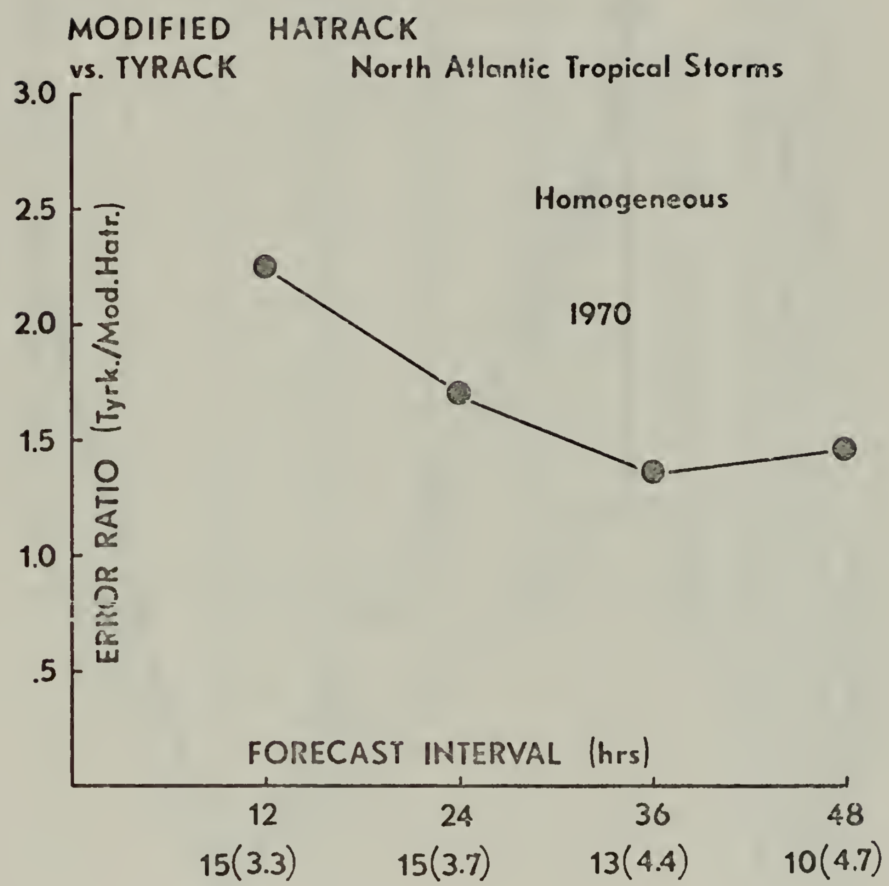



Fig. 13 Similar to Fig. 12, except a homogeneous comparison.

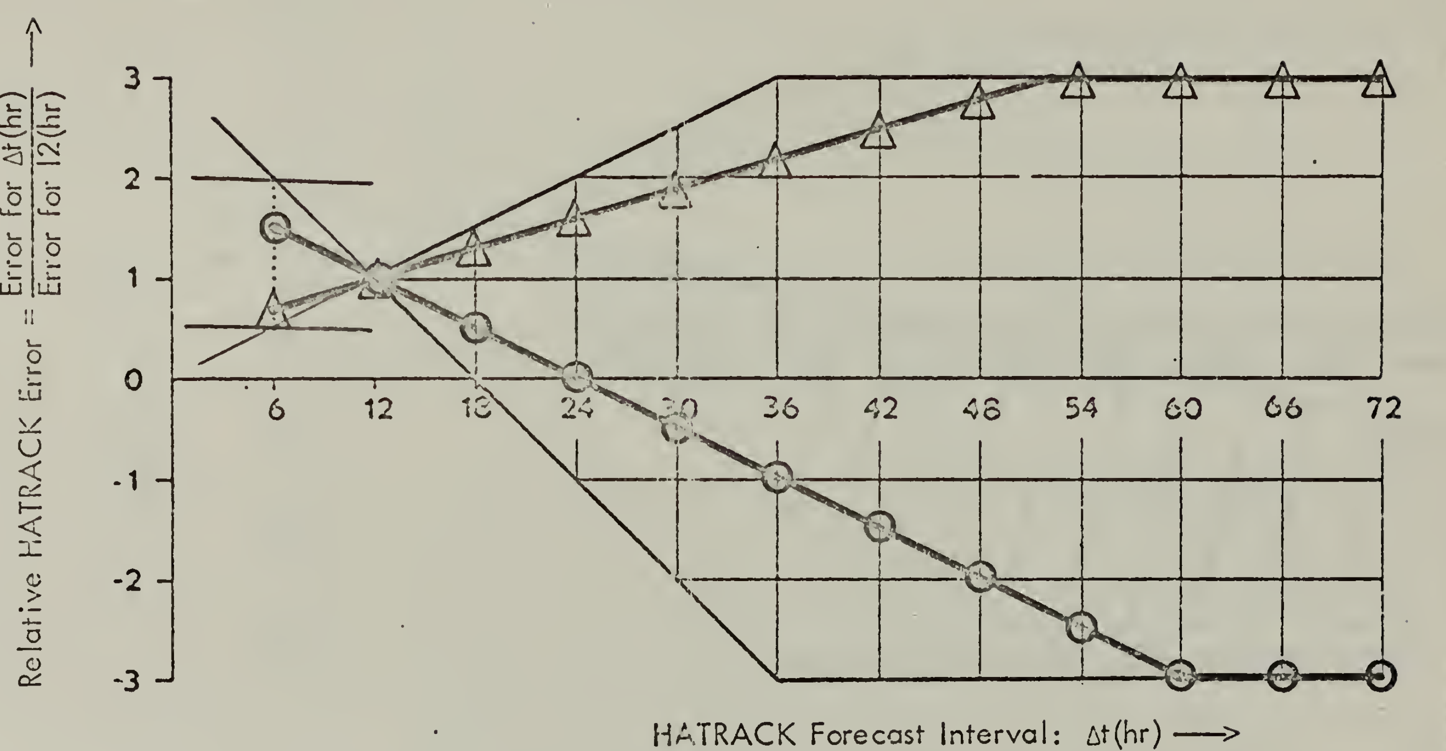



Fig. 14 Diagram for graphically computing the forecast relative HATRACK error as a function of the HATRACK forecast interval. The linear curves illustrate typical latitude (Δ-Δ-Δ) and longitude (0-0-0) relative error extrapolations.

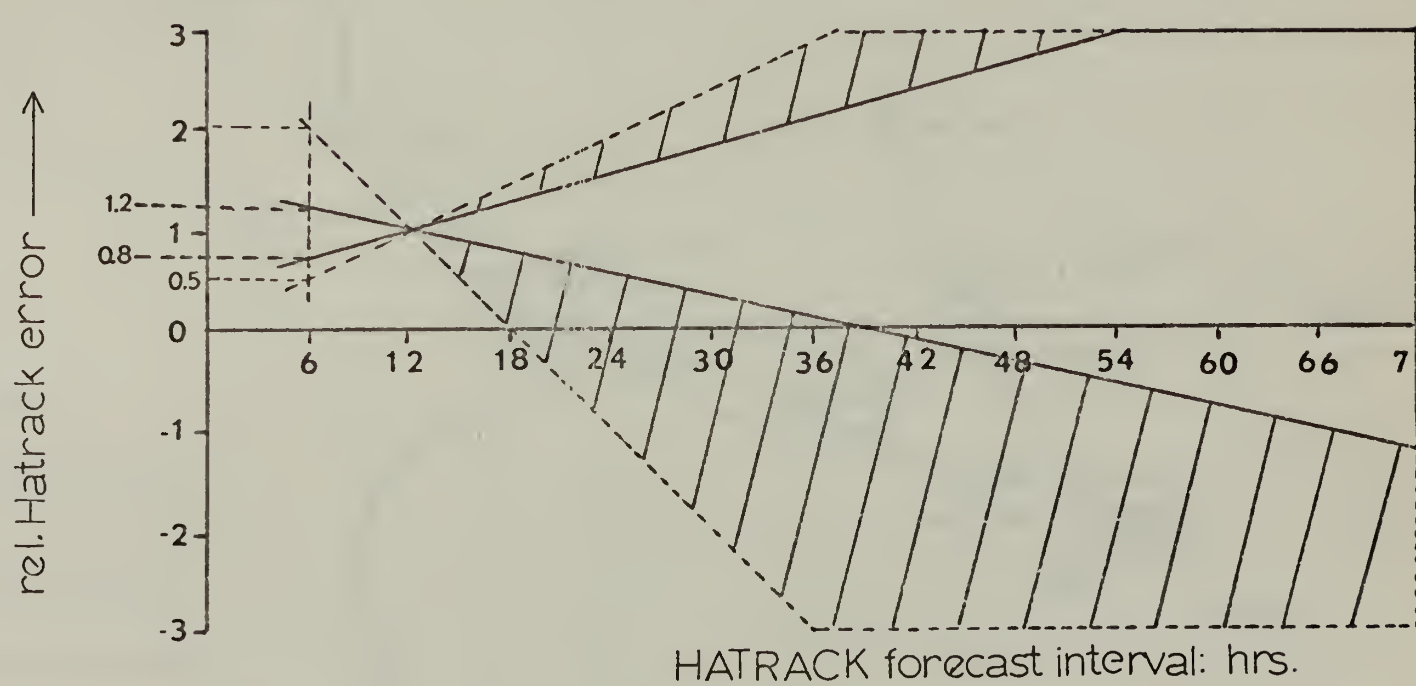



Fig. 15 Diagram showing a comparison of allowable relative error forecasts as a function of relative error limits at six hours. For limits of 0.5 to 2.0, hatched and clear enclosed areas apply; for limits of 0.8 to 1.2, only the clear enclosed area applies.

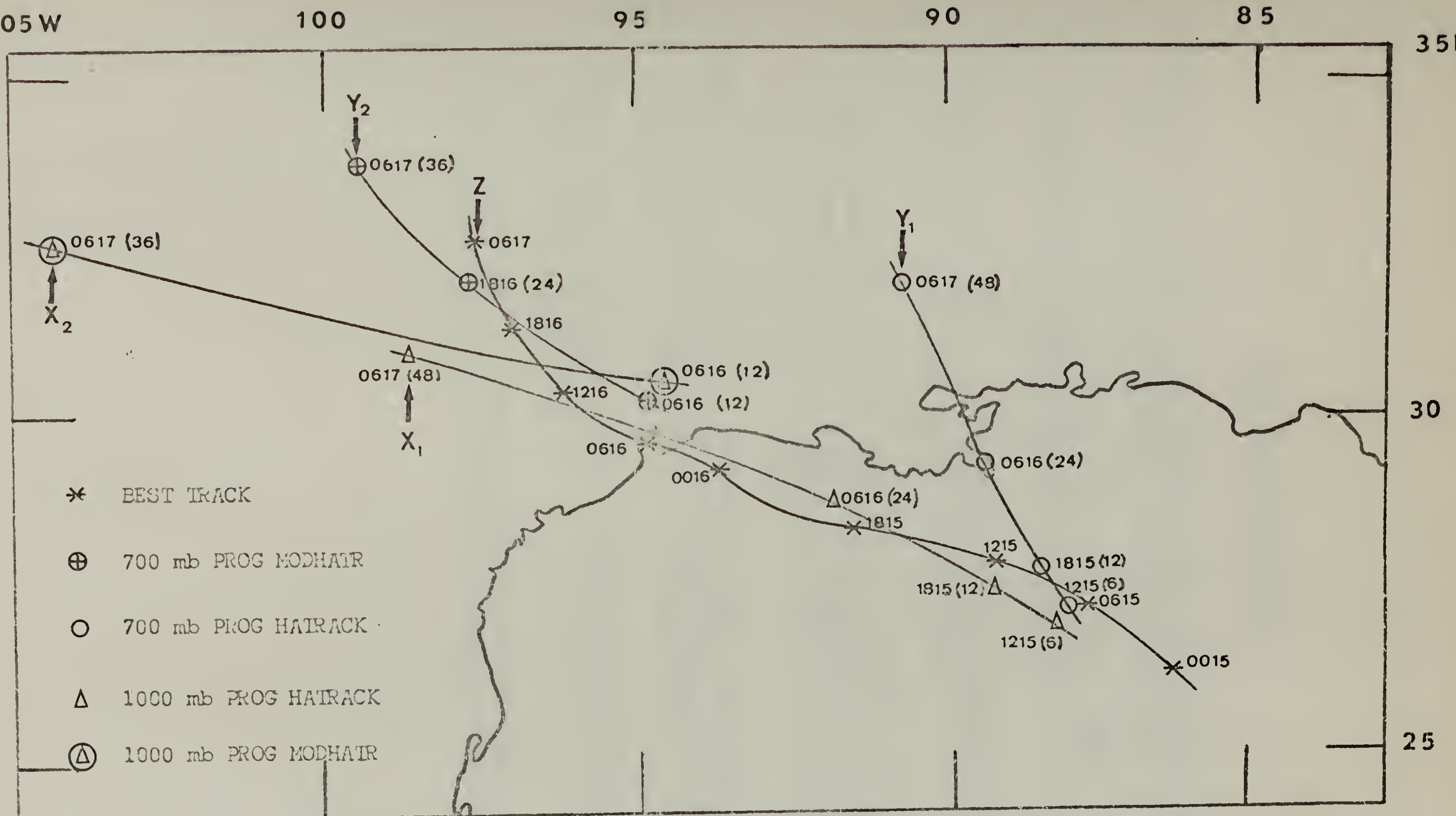



Fig. 16 Plot of typical case showing the effect of the modification component on a 700 mb prog-mode HATRACK forecast set and a best-level/mode HATRACK forecast set.

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3. REPORT TITLE

Further Verifications of and Experiments to Improve the Modified Hatrack Scheme for Forecasting the Motion of Tropical Cyclones

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Master's Thesis; September 1971

5. AUTHOR(S) (First name, middle initial, last name)

Stephen Gregory Colgan

| 6. REPORT DATE | 7a. TOTAL NO. OF PAGES | 7b. NO. OF REFS |
|---|---|---|
| September, 1971 | 57 | 7 |

| | |
|---|---|
| 8a. CONTRACT OR GRANT NO.<br>b. PROJECT NO.<br>c.<br>d. | 9a. ORIGINATOR'S REPORT NUMBER(S)<br>9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) |

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13. ABSTRACT

The MODIFIED HATRACK(MODHATR) scheme for forecasting tropical cyclone motion consists of a numerical steering component using geostrophic winds derived from Fleet Numerical Weather Central's SR height field to steer the storm center, and a statistical modification component to correct for bias and improve forecast accuracy. MODHATR forecasts from the1969 and 1970 North Atlantic hurricane seasons are analyzed, and average errors presented and compared to earlier years'results. MODHATR forecasts are shown to be superior on the average to OFFICIAL forecasts, NHC-67, and TYRACK forecast schemes for forecast intervals to 48 hours, with relative accuracy of MODHATR decreasing with time.

Results of an experiment to improve the statistical correction for bias are reported. A level-and mode-selection scheme is investigated which offers some promise of improving forecast accuracy at later forecast intervals. A comparison is made between warning-time and synoptic-time initial-position errors showing synoptic-time positions to be more accurate for initiating MODHATR forecasts.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6811



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|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| MODIFIED HATRACK | | | | | | |
| HATRACK | | | | | | |
| Forecasting hurricane movement | | | | | | |
| Tropical Cyclones | | | | | | |
| Atlantic Hurricanes | | | | | | |
| Hurricanes | | | | | | |

Thesis
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Colgan
Further verifications of and experiments to improve the modified hatrack scheme for forecasting the motion of tropical cyclones.